ESTIMATION OF MINE CASE BURIAL IN A MUD-COVERED SEA BOTTOM USING ACOUSTIC IMPEDANCE VALUES OBTAINED FROM A SHIPBOARD FATHOMETER

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ABSTRACT

A 12 kHz Bottom Sediment Classification (BSC) system that characterizes the sea-bottom according to acoustic impedance estimates was used to obtain normal incident acoustic data for determination of bottom sediment composition in Southeast Pass Louisiana, near the mouth of the Mississippi River, and in an area offshore Corpus Christi Texas.

The BSC uses the bottom and subbottom echo from a hull mounted transducer or transducer array to determine the acoustic impedance of the upper 50 cm of the sediment beneath the ship. A two-dimensional display of the sediment profile along track and a plot of the ship tracks, colorized to represent the composition of the seafloor, are provided in real-time to enable shipboard personnel to estimate bottom composition while the ship is underway. Acoustic data and screen images of the acoustic profiles are recorded to hard disk for additional review, data archiving, and post-mission laboratory analysis. A similar version of this system using Through-The-Sensor (TTS) technology has been successfully demonstrated aboard four US Navy mine countermeasures (MCM class) ships over the past three years.

Predictions of bottom composition, i. e. sand or mud, provided on the BSC displays were used to select sites for an impact burial prediction study using cylindrical mine-like shapes. Approximately forty-eight separate cylinder deployments were conducted in muddy sea-bottoms at several different locations within two study areas in East Bay Louisiana and near Corpus Christi Texas. Subsequent to deployment, divers measured and recorded penetration depth of each shape in the seafloor. Sediment samples obtained by gravity and diver cores at each deployment site were used for ground truth assessment of sediment physical and geo-acoustic properties. Acoustic impedance values calculated from these properties were compared to the measured burial depths of the cylinders at both sites. The resultant empirical fit provides a feasible beginning for using this technique whereby the impedance values calculated from acoustic data obtained by the sediment classifier are used to predict impact burial depth in muddy sediment environments.

I. INTRODUCTION

Bottom composition in shallow water regions where MCM operations are conducted can be highly variable in both space and time. This variability complicates the difficult task of locating and neutralizing any mines that may have been laid on or buried upon impact with the sea bottom. Therefore, a capability to predict impact burial potential of bottom mines before MCM operations occur can be of critical importance to the success of the MCM mission. Tactical considerations such as whether to hunt or sweep, or avoid an area completely could be made solely based on determining the likelihood of impact burial using a pre-mission bottom classification survey.

MCM planners use historical bottom sediment data that describes regional distribution of composition types (i. e. sand and mud) for predicting where impact burial of bottom mines is likely to occur. However, sparse sampling frequency and complex spatial and temporal dynamics in shallow water regions can lead to possible interpretation errors. These errors may provide inadequate characterization of bottom composition to accurately predict impact burial potential of bottom mines over spatial scales required for MCM operations. It is imperative that MCM operators know where impact burial of bottom mines is likely to occur before and during their operations, especially in regions where soft, muddy sediments are common.

Archived, historical sediment density and grain size data are typically used to calculate predictions of impact burial potential of bottom mines during a pre-mission, regional, planning phase. However, more detailed coverage and continual monitoring of impact burial potential along planned routes would be advantageous, and in fact is needed, especially during site survey or other MCM operations. Typically, sediment property data are not available to or exploitable by MCM operators in real-time; however, the ability to visually characterize and graphically display estimates of bottom composition along the ship track can provide important information and perspective for assessing the potential for impact burial of mines within the battle-space environment.

In the past we have used a prototype bottom sediment classification system interfaced with an existing organic fathometer to estimate bottom composition aboard several US Navy MCM 1 class vessels (Fig. 1). The bottom profile and sediment composition (i. e. sand or mud) are presented on the real-time visual displays that can be used to assess the potential for impact burial of bottom mines.

II. BACKGROUND

Use of a bottom sediment classifier integrated with the standard UQN-4A Fathometer (AN/UQN-4A – Sonar Sounding Set) was demonstrated aboard the USS CHAMPION for a six month period during late CY2000 and early CY2001 [1] and aboard the USS DEXTROUS (MCM-13) in the Arabian Gulf between OCT 2001 and JUL 2003 [2]. Additional, temporary, installations using a laptop computer have also been accomplished on the USS SENTRY (MCM 3) and the USS SCOUT (MCM 8).

In these applications, the Bottom Sediment Classifier (BSC) provides a real-time visualization of the sediments at and below the sea bottom and a related map that illustrates the surficial sediment composition along the ship track based on acoustic impedance values[1] inverted from the bottom reflection coefficient of the upper 50 cm of sediment. The BSC predicts the acoustic impedance (the product of density and sound velocity) in real-time, providing an estimate of bottom hardness that is related to bottom composition used in MCM Doctrine, i.e. sand and mud. This is accomplished by comparing the impedance predictions with data tables that were derived empirically from analysis of continental shelf sediments [3], [4], [5].

Typically, two image types are presented in real-time while the ship is underway (Fig. 2). The first display provides a scrolling, cross-sectional profile for “visualizing” the sea bottom beneath the ship. Position information is written to the screen automatically as the image scrolls to the left. Each full screen width of the data is saved automatically as a .JPG image (file) into a picture directory for immediate or post-operation review. The vertical axis on these displays represents depth below the keel and the horizontal axis represents distance along track. Both scales are labeled on the screen as the image is displayed. The vertical axis is user adjustable and has an optional auto-scale feature. The acoustic data are presented in a color that represents the intensity of the acoustic signal returned from the sea bottom and below in steps of 6 dB down from the maximum output intensity of the sonar. A color reference bar is provided on the right side of the display that equates the return signal intensity levels in the specified colors. The colors at the top of the bar represent hard sediments; white, gray, purple and dark red portray high intensity return from hard bottoms, whereas the colors at bottom of the bar are indicative of soft sediments; e.g. light red, yellow, green, and blue indicating low return intensity. A second image shows the ship’s present and

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[1] The units are 10^6 kg m^{-2} s^{-1}.

past position on a two-dimensional, geo-referenced, map display as it proceeds along a track. The ship track-line is colored in accordance with the sediment impedance predicted by the BSC. A color key of bottom composition, based on the BSC predicted acoustic impedance, is also provided on this display. This key essentially defines the sediment composition based on estimates of acoustic impedance obtained from the intensity of the signal return from the bottom. The key is related to the sediment composition based on the empirical relationships described above, in particular, the relationship defined by Hamilton and Bachman (1982) between acoustic impedance and sediment grain size. For this application the color scale is partitioned into segments that represent sand or mud. Therefore, hot colors (purple, red) indicate hard sediments (usually sand) and cool colors (green, blue) represent soft sediments (mud). This mapping process also provides a reliable representation of the relative changes in surficial sediment distribution encountered along a survey route.

II. FIELD EXPERIMENTS

Several experiments were conducted over the past few years where repetitive deployments of full scale, instrumented, mine-like cylinders were used (Fig. 3). These experiments were conducted to collect and systematically analyze and quantify the complex three-dimensional behavior of the instrumented cylinders during freefall through the water-column and penetration into the ocean bottom. The objective was to conduct statistical analysis of the trajectory and embedment data to construct a robust and reliable numeric model to quantitatively predict the potential for impact burial of bottom mines.

Abelev and Valent [6] conducted these experiments and provide a detailed analysis of the complex dynamic processes taking place during the deployment, free-fall and impact of the cylinder on and burial in the seafloor. Rather than trying to model the complex processes involved in the cylinder deployment, we are attempting to generate an empirical relationship between the sediment properties and the final burial resulting from these processes. We recognize that fluctuations in angular trajectory through the water column, nose type, weight distribution, and deployment method will result in considerable scatter in burial measurements which are unrelated to sediment properties. Such variation might be expected in operational deployments as well. However, we attempt to determine if knowledge of sediment properties will allow us to place limits on the mine burial. Only the percent volume of the cylinder buried in the seafloor and the acoustic properties of the seafloor itself are considered in this study. Divers measured the maximum amount of the cylinder exposed above the mean sediment floor level. The final buried volume was calculated from this measurement and the orientation angle obtained from the cylinder instrumentation.

A total of thirty-seven cylinder deployments were made in East Bay (EB) near Southeast Pass Louisiana, a birdfoot delta located near the mouth of the Mississippi River while eleven additional drops were conducted in another area further west, offshore Corpus Christi (CC) Texas (Fig. 4). At both locations, acoustic data were obtained along tracks in close proximity to the cylinder, core and diver deployment sites. The acoustic system aboard the R/V GYRE during the study off Corpus Christi Texas consisted of an AN/UQN-4 fathometer integrated with the NRL Acoustic Seafloor Classification System (ASCS). The UQN-4 transducer (TR-192B) was mounted in a moon-pool in the ship's hull. The same ASCS electronic interface package was used aboard the R/V PELICAN during the study in East Bay, however, a commercial power amplifier was to drive the ship's permanently hull-mounted transducer. Both systems used the same frequency (12 kHz), pulse length (0.33 ms), power levels and waveforms.

III. CYLINDER BURIAL MEASUREMENTS AND SEDIMENT IMPEDANCE CALCULATIONS

As expressed previously, Abelev and Valent's treatment of the complex dynamics leading to impact burial is quite extensive. Our analysis took a more pragmatic approach, considering first the relationship between the specific sediment and the actual burial depth of the cylinder in the sediment. The idea is to relate the measured volume of cylinder buried beneath the seafloor to the acoustic impedance values derived from the measured wet bulk density and compressional wave velocity in sediment cores that were collected at the same locations as the cylinder deployment sites.

A GeoTek Multi-Sensor Core Logger® was used to measure both wet bulk density and compressional wave velocities at 1 cm intervals along the length of each core. Calculating the product of these values yields an acoustic impedance for each sample interval. The impedance values for the upper 50 cm were then averaged to derive a representative impedance value for that segment of the core. Values of the wet bulk density and the compressional wave velocities within the same core segment (0 – 50 cm) were also averaged to provide a representative value for each property for the same segment. The product of these averages was then compared to the average of the calculated impedances. This averaging resulted in an insignificant difference of less than a 0.25 percent between the impedance values derived by the two different averaging techniques. Therefore, the impedance derived from the average of all the calculated impedances, i.e. the first averaging technique described above, was used.

The sediment sample impedance values were then plotted against the percent volume buried of each cylinder at the same location (Fig. 5). The range of the data obtained from the two, distant (≈ 800 km), offshore environments are limited and have values for impedance ranging between 2.07and 2.16 in East Bay to a higher range of 2.24 to 2.60 in the Corpus Christi data. Likewise, wet bulk densities ranged between 1.5 – 1.7 g/cm^3 and the compressional wave velocities were between 1490 and 1530 m/sec. As a result, the two data sets provide a limited capability to derive a useful regression due to the limited range of the calculated sediment impedance values. The lack of burial or sediment data from an area where little or no burial was measured or expected limits our ability to extend the relationship to these areas. Bottom sediments in an area such as this would most likely include predominantly sandy bottoms with limited mud content and range upward into a harder bottom that will not allow burial on impact.

Interestingly the data points on the graph are grouped with samples according to their location, i.e. none of the data from the East Bay site fall near the data from the Corpus Christi site. The East Bay data set (EB) is shown with the highest measured percent burial and lowest impedance values while the Corpus Christi data have the lowest percent of measured burial and the highest impedance. Fitting a curve through the East Bay and Corpus Christi (CC) data generates a regression that is somewhat restricted and not valid for bottom types other than these muddy regions. Additional data from mixed sediment, mid-impedance, and sandy, high impedance bottoms could improve the application of this technique and impart a higher level of confidence for applying the technique.

IV. ACOUSTIC IMPEDANCE AND IMPACT BURIAL PREDICTIONS

The acoustic data was processed in the laboratory to extract co-registered, impedance values and position data along ship tracks that passed in close proximity to the deployment sites. Figures 6 and 7 show the ship tracks and nearby cylinder deployment and sediment sample locations at the East Bay and Corpus Christi sites, respectively. The ship track, colored according to the impedance value at each location along the track, shows that although the impedance measurements along track vary slightly, a range of impedances can be used here to compare the track impedance data with the impedance measurements at the coring sites. As observed on the maps, the ship tracks did not cross directly over most of the exact deployment sites and averaging may provide a reasonable mechanism to relate the BSC impedance values with those of the cores. However, we can use the range of impedance values in lieu of averaging to determine the minimum and maximum predicted burial at several points along the regression identified in Figure 5.

Examples of the acoustic imagery for a representative segment in each region near the sampling sites are provided in Figures 8 and 9. Figure 8 was created during post-processing and covers approximately 0.5 km along the segment of the track indicated by the rectangular box in Figure 6. Figure 9 is the real-time image obtained at sea in that the portion of the track identified by the open circle in Figure 7, covering a distance of approximately 0.75. Examining these figures provides a mechanism to assess the bottom composition at these locations. The intensity of the acoustic return at the sediment/water interface is indicated by the color of the return. White, gray, purple and dark red indicate a high impedance, hard bottom; whereas light red, yellow, green, and blue are indicative of low impedance/soft sediments. The return intensity in Figure 9 from the Corpus Christi site is 18 dB higher than that in Figure 8 from the East Bay site indicating that the sediment at this location in the Corpus Christi area is more firm than that observed in the image from the East Bay site.

The color of the tracks in Figures 6 and 7 characterize the bottom composition based on the impedance value of each data point (acoustic shot) along the track. The color key provides the range of impedance values for each color. This map provides a mechanism to utilize the impedance values from the acoustic data along each track to calculate the impact burial predictions. The impedance range values are used with the regression in Figure 5 and empirically compared to burial depths measured during the at sea experiments. An estimate of the predicted impact burial is then obtained by using the average impedance ranges at any point along the track with the equation provided by the expression defined by the regression;

$$[1] \qquad y = -162.59x + 437.35.$$

The predominant color along each track indicates that the impedances are greater than 1.8 but less than 2.2 for most of the East Bay site. They are slightly higher at the Corpus

Christi sites ranging between 2.2 and 2.7 at the two areas further offshore and higher at the third, closer to shore, site (between 2.7 and 3.2)! Using expression [1], the predicted impact burial at any of these sites would be eighty percent or more below an impedance of 2.2 and higher impedances of 2.3, 2.4 and 2.5 would have impact burial estimates of sixty-three, fifty, and thirty-one percent, respectively. Since no data is available from either site in excess of

V. SUMMARY

We have attempted to generate a relationship between impact burial depths of mine-like cylindrical shapes and the acoustic properties of the upper sediment volume into which they are implanted. After conducting several impact burial experiments and obtaining ground truth sediment property data with bottom cores, the sediment data and diver measured burial characteristics were graphically compared to determine if the two showed any signs of correlation. After this brief investigation it seems feasible to use the acoustic impedance calculated from the product of the measured compressional wave velocity and wet bulk densities of the sediment core samples obtained at several mine burial sites to describe a relationship with the measured depth of burial to the mine-like cylinder at the same sites. However, the initial approach of using only two data sets from similar muddy bottoms presented a significantly limited relationship between the target properties because the impedance values ranged only between a low of approximately 2.1 and a high of 2.6. Fitting a regression between these values artificially restricted the scope of the application to a smaller range than can be expected in marine environments, but, these regions are the most important when considering impact burial potential! Obviously, further work is needed to populate the graph with additional data from hard bottom areas where actual impact burial depths can be measured and from sites that represent the transition on the graph between the very soft bottoms that were sampled during the two original studies and the hard bottom sites. This application was used for cylindrical shapes only and did not account for changes in nose configurations. Additional field work and studies are needed to integrate other configurations and shapes into the same or, most likely, separate regressions for each configuration.

Finally, if, after further data population and expansion into other configurations, it is shown that empirical relationships are valid and useful tools for impact burial predictions, they could be easily adapted for use with the AN/UQN-4A Bottom Sediment Classifier (BSC). Integration of this system with the existing Battle Space Profiler (BSP - a profiling

Conductivity, Temperature, and Pressure instrument) presently used onboard all US MCM-1 and MHC-51 class vessels is planned. This will provide a real-time tactical capability to predict impact burial potential before and during the conduct of MCM operations.

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As any experimental study performed at sea, the success of this research would not be possible without the contributions of many people, including to C. Kennedy, C. King, C. Vaughn, G. Bower, M. Richardson, K. Briggs, R. Ray (all NRL), the captains and crews of the R/V Pelican (Cocodrie) and R/V Gyre (Corpus Christi), and many others.

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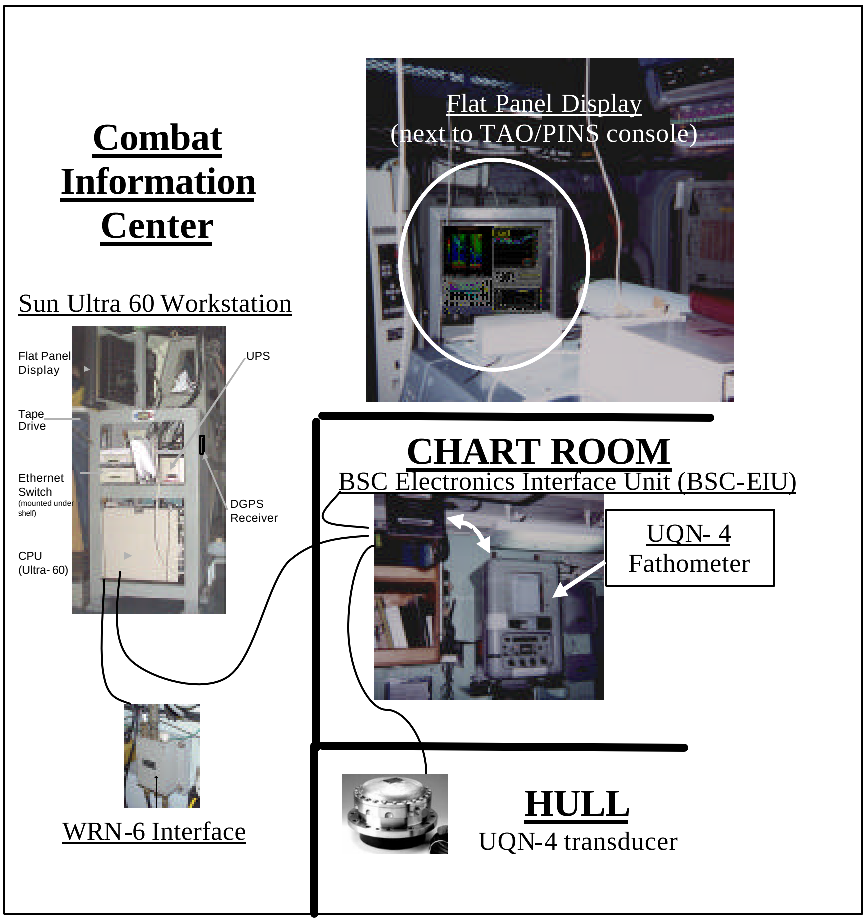
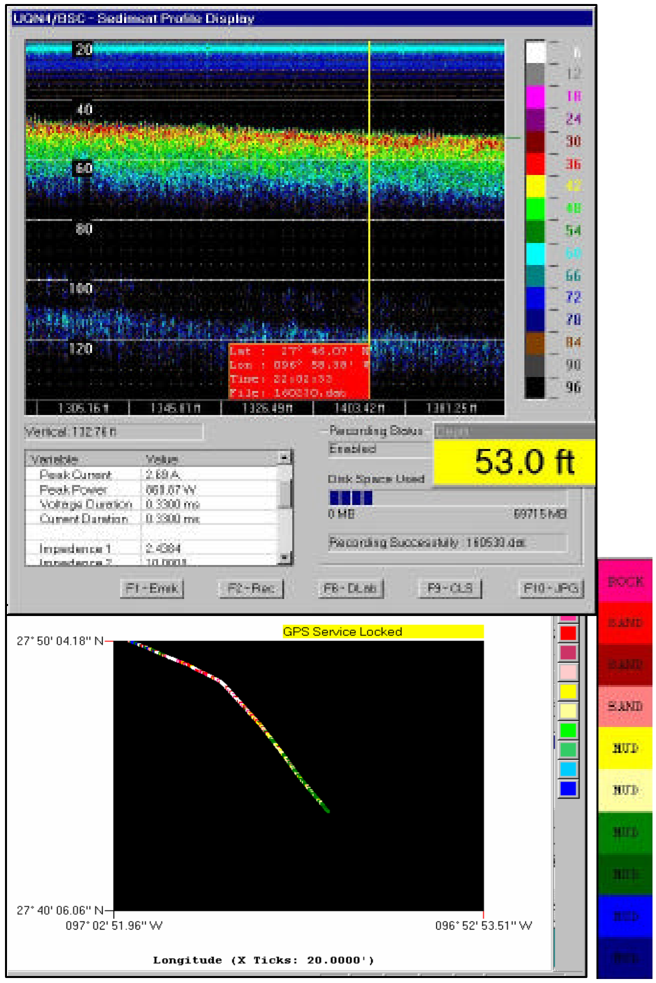


Figure 1. AN/UQN-4A Bottom Sediment Classifier (BSC) physical configuration aboard an MCM-1 class vessel.

(a) Bottom Sediment Profile



(b) Ship Track/Sediment Property

Figure 2. Two representative Bottom Sediment Classifier (BSC) displays as presented on the Flat Panel Monitor of the Sun Workstation in the MCM ship Combat Information Center. The Sediment Profile Display (a) is similar to other fathometer/seismic data displays that visualize a cross-section of the sediment column beneath the ship. The vertical depth scale is indicated by the gray horizontal lines and labeled in meters beneath the keel. The horizontal distance scale (also in meters) is located at the bottom of the black window and specifies the along track distance between the small vertical white lines. The yellow vertical event mark and the associated small red box are written on the right side of the screen automatically as it scrolls to the left. Information provided in the box designates the file name and position and time information at the event mark. The vertical color bar at right is shown steps of 6 dB per color representing the intensity of the acoustic return. Likewise, the Ship Track/Sediment Property Display (b) has a color scale that represents the bottom composition type based on the impedance value calculated by the BSC. The composition terminology is the same as that used in Mine Warfare Doctrine, i.e. sand or mud. Latitude and Longitude ranges are provided on the x and y axes, respectively.

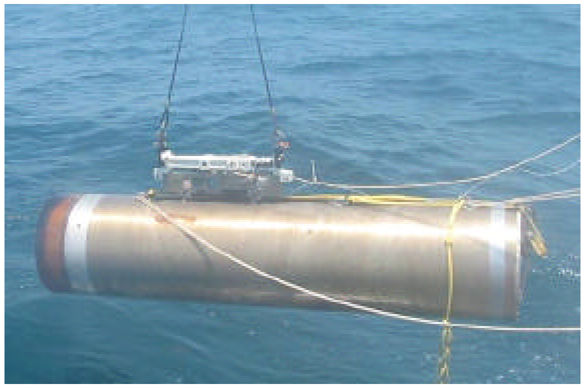


Figure 3. Instrumented cylinder with the blunt nose attached, before an air release.

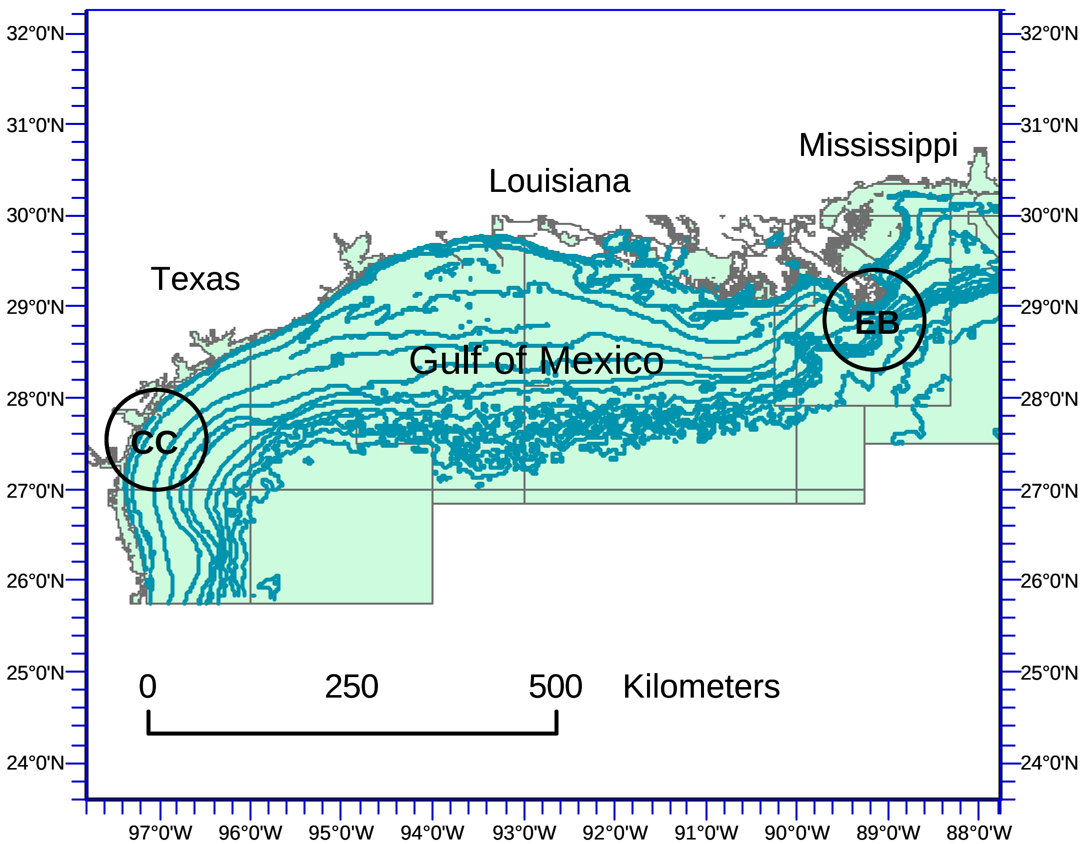


Figure 4. Location of the two study sites in the northern Gulf of Mexico near Corpus Christi Texas (**CC**) and in East Bay offshore Louisiana (**EB**).

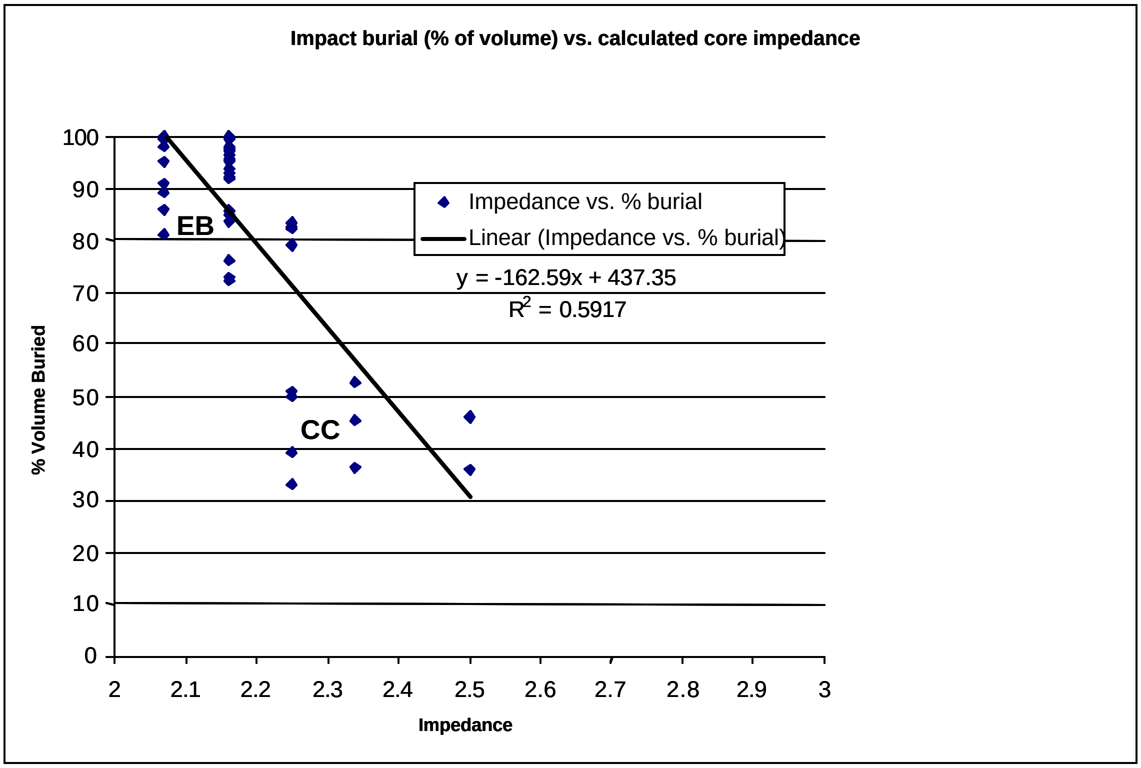


Figure 5. The black diagonal line represents a linear fit (y = -162.59x + 437.35) through the measured impedance and associated impact burial data from the two sites. Using the equation for the regression with the impedance value obtained from the BSC renders a percent impact burial potential for that impedance.

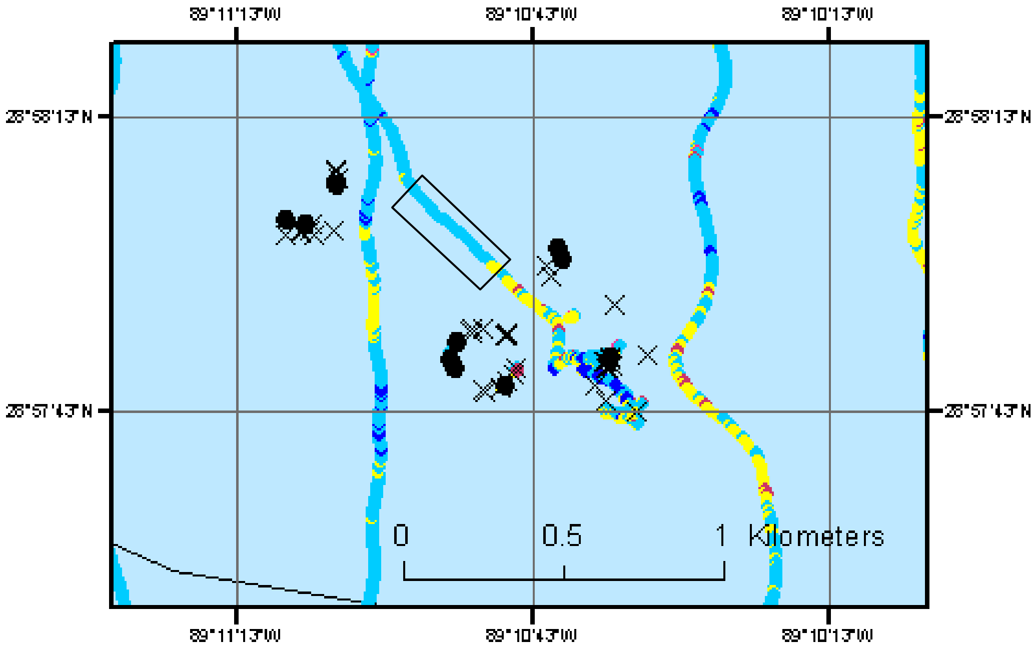


Figure 6. Map showing cylinder deployment sites (X), core collection sites (●), and color coded* ship tracks where the Bottom Sediment Classifier collected acoustic data. The area of coverage for the BSC image in Figure 8 is indicated by the rectangular box along the diagonal track.

* Color Key (impedance value range):

- ● >1.5 to 1.8
- ● >1.8 to 2.2
- ● >2.2 to 2.7
- ● >2.7 to 3.2

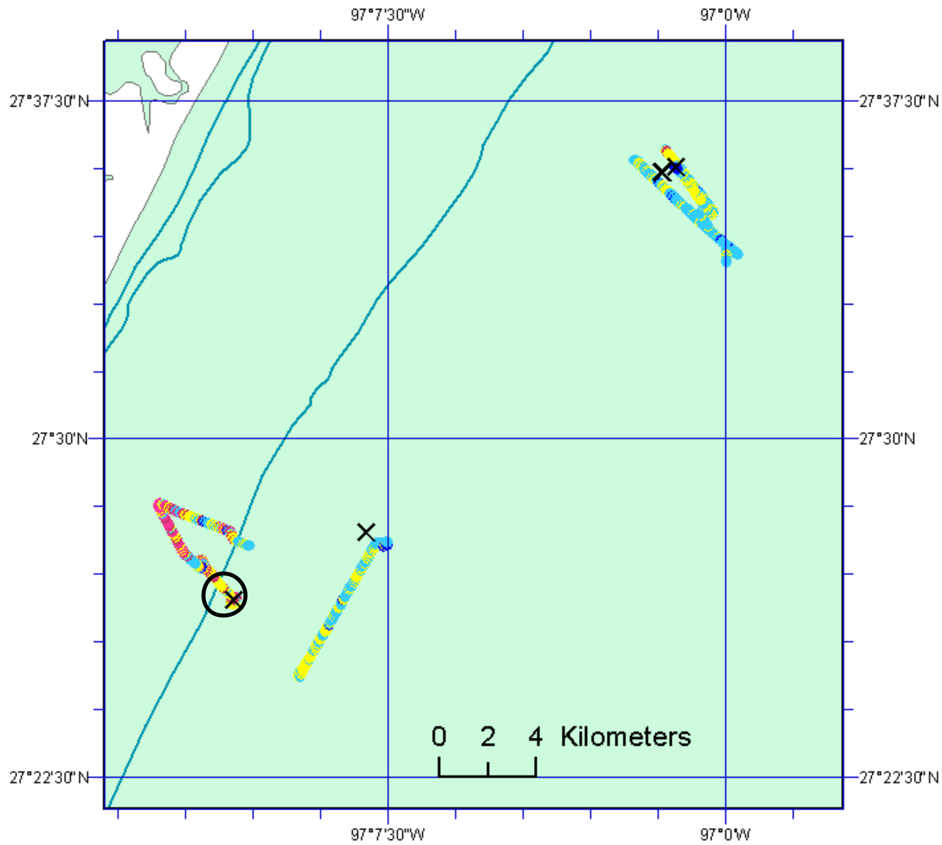


Figure 7. Map showing co-located core collection sites (X) and cylinder deployment sites. The colored lines* are where the Bottom Sediment Classifier data were obtained. The location of the BSC image in Figure 9 is indicated by the black circle.

* Color Key (impedance value range):

- ● >1.5 to 1.8
- ● >1.8 to 2.2
- ● >2.2 to 2.7
- ● >2.7 to 3.2

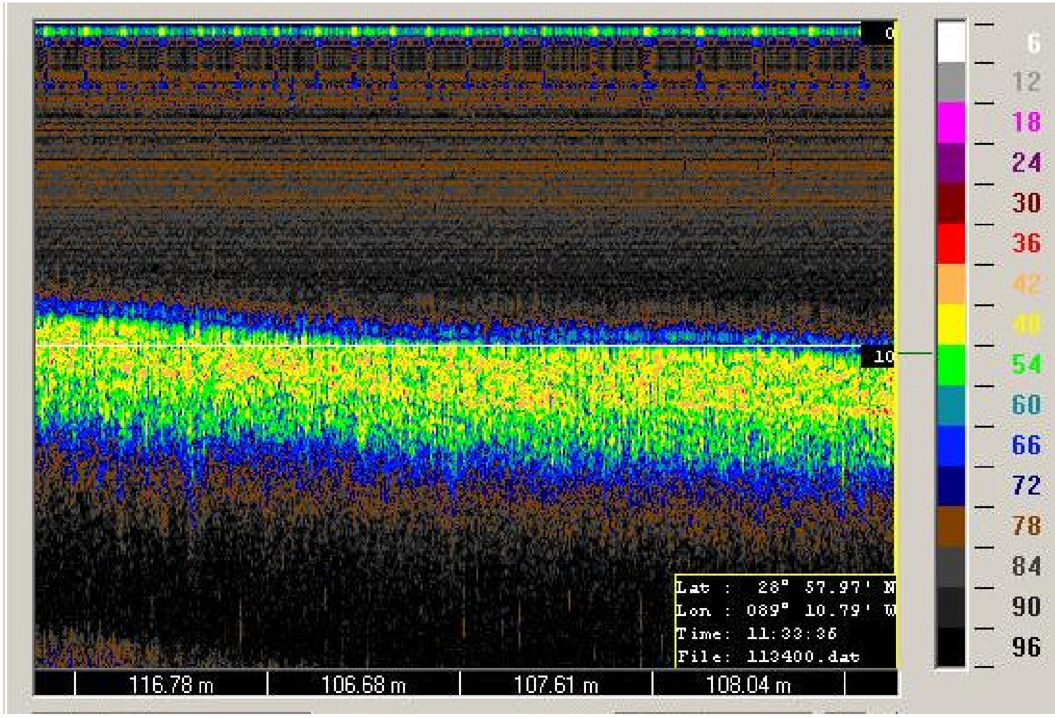


Figure 8. BSC image indicating a soft bottom created during post-mission analysis of East Bay Louisiana data. Bottom return is at the 54 dB level with diminishing return to 5 m beneath the sediment/water interface and little to no return beyond that!

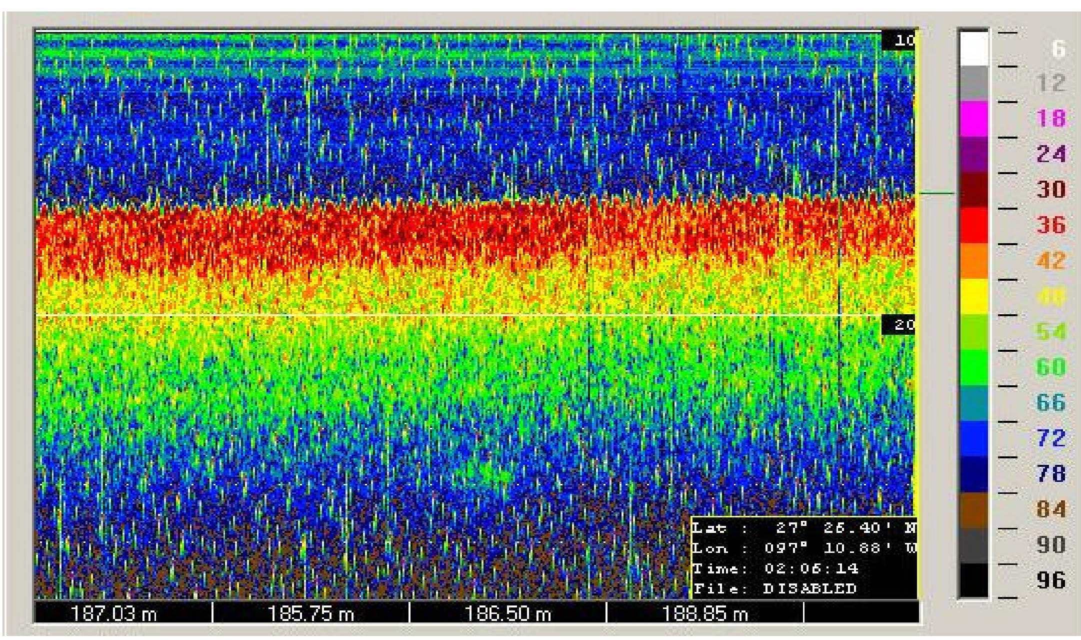


Figure 9. Representative BSC profile indicating soft bottom obtained off Corpus Christi Texas. As indicated by the different color this bottom is harder than that shown in Figure 8. Return intensity beneath the sediment/water interface is also higher at this site than at the East Bay site.